Open Charm and Beauty at Ultrarelativistic Heavy Ion Colliders

Magdalena Djordjevic,[1] Miklos Gyulassy,[1] and Simon Wicks[1]

[1]*Department of Physics, Columbia University, 538 West 120-th Street, New York, NY 10027*

(Dated: February 7, 2008)

Important goals of RHIC and LHC experiments with ion beams include the creation and study of new forms of matter, such as the Quark Gluon Plasma. Heavy quark production and attenuation will provide unique tomographic probes of that matter. We predict the suppression pattern of open charm and beauty in $Au+Au$ collisions at RHIC and LHC energies based on the DGLV formalism of radiative energy loss. A cancelation between effects due to the $\sqrt{s}$ energy dependence of the high p_T slope and heavy quark energy loss is predicted to lead to surprising similarity of heavy quark suppression at RHIC and LHC.

PACS numbers: 12.38.Mh; 24.85.+p; 25.75.-q

Introduction. RHIC and LHC experiments involving nuclear collisions are designed to create and explore new forms of matter, consisting of interacting quarks, antiquarks and gluons. One primordial form of matter, called the Quark Gluon Plasma (QGP), is believed to have existed only up to a microsecond after the "Big Bang". If this QGP phase can be created in the laboratory, then a wide variety of probes and observables could be used to diagnose and map out its physical properties.

The striking discoveries [1] at Relativistic Heavy Ion Collider (RHIC) of strong collective elliptic flow and light quark and gluon jet quenching, together with the decisive null control $d+Au$ data, provide strong evidence that a strongly coupled Quark Gluon Plasma (sQGP), is created in central $Au+Au$ collisions at $\sqrt{200}$ AGeV with gluon densities 10-100 times greater than nuclear matter densities [2]. While there has been considerable convergence on the theoretical interpretation [3] of RHIC data, the experimental exploration of the sQGP properties beyond the discovery phase has barely begun [4]. Future measurements of rare probes such as direct photons, leptons, and heavy quarks will help to more fully map out the sQGP properties and dynamics.

Heavy quarks provide important independent observables that can probe the opacity and color field fluctuations in the sQGP produced in high energy nuclear collisions. In this letter, we present predictions of open charm and beauty quark suppression that can be tested at both RHIC and the future LHC facilities. Together with the already established light quark and gluon jet quenching and collective elliptic flow, a future observation of a reduced heavy quark suppression (as compared to the observed pion suppression) could strengthen the current case for sQGP formation as well as test the evolving theory of jet tomography [5].

The prediction of D and B meson suppression pattern, in principle, requires theoretical control over the interplay between many competing nuclear effects [6] that can modify the $p_\perp$ hadron spectra of heavy quarks. To study the high $p_\perp$ ($p_\perp > 6$ GeV) heavy quark suppression, we concentrate on the interplay between two most important effects, i.e. jet quenching [5, 6] and energy dependence of initial pQCD heavy quark $p_\perp$ distribution. In addition, we explore a range of initial conditions at LHC based on extrapolating RHIC data [7] and based on Color Glass Condensate effective theory [8]. We note that, for lower $p_\perp < 6$ GeV spectra nonperturbative effects neglected here, for example collective hydrodynamic flow, quark coalescence and the strong gluon shadowing in the initial CGC state, may become important [3].

Theoretical framework. To compute the heavy quark meson suppression we apply the DGLV generalization [10] of the GLV opacity expansion [9] to heavy quarks. We take into account multi-gluon fluctuations as in [11]. To apply this method, we need to know the following: 1) Initial heavy quark $p_\perp$ distribution, 2) Difference between medium and vacuum gluon radiation spectrum and 3) Heavy quark fragmentation functions.

The initial heavy quark $p_\perp$ distributions are computed using the MNR code [12]. As in the [13], we assume the charm mass to be $M_c = 1.2$ GeV and beauty mass $M_b = 4.75$ GeV. We assume the same factorization and renormalization scales as in [13]. For simplicity, we have concentrated only on bare quark distributions ($< k_\perp^2 >= 0$ GeV^2), and the runs were performed by using CTEQ5M parton distributions.

Fig. 1 shows initial $p_\perp$ distributions for D and B mesons. By comparing $p_\perp$ distributions at RHIC and LHC case we see that RHIC distributions have significantly larger slope than the LHC ones. Since the suppression is sensitive to the slope of quark initial $p_\perp$ distribution, the decrease in the $p_\perp$ slope with the increase of collision energy will have the tendency to lower the suppression from RHIC to LHC.

Additionally, comparison between full and dashed curves on Fig. 1 shows the variation of D and B meson $p_\perp$ distributions using two different types of fragmentation function. Full curves show meson spectrum obtained by using δ-function fragmentation, while dashed curves show meson spectrum obtained using the Peterson fragmentation [14]. Though the choice of fragmentation function can lead to the order of magnitude difference in the absolute $p_\perp$, we see that slopes of the curves remain quite similar. Therefore, we expect that the final suppression is insensitive to the choice of fragmentation functions. This

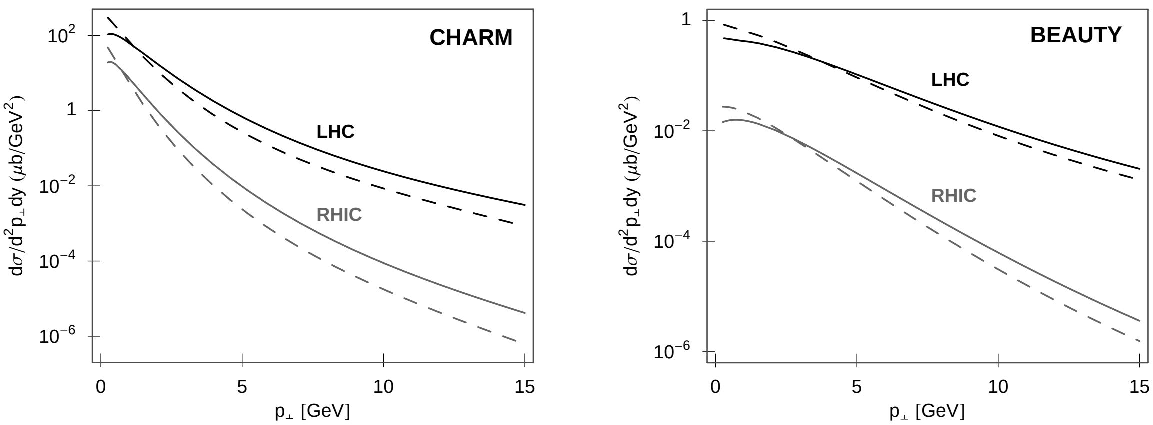

FIG. 1: Initial $p_\perp$ distributions are shown for D (left figure) and B mesons (right figure). Lower (upper) curves correspond to RHIC (LHC) case. Solid curves are computed by assuming δ-function fragmentation while dashed curves assume Peterson fragmentation [14]. For D (B) mesons we used $\epsilon = 0.06$ ($\epsilon = 0.006$) [13].

conclusion is confirmed in Fig. 4 below, difference of less than 0.05 in the nuclear modification factor R_{AA} is found. (R_{AA} is the ratio of the observed yield in $A+A$ divided by the binary collision scaled yield in $p+p$.) Therefore, for clarity, we show most results only for δ-function fragmentation for both charm and beauty quarks.

To compute the gluon radiation spectrum, we have to include (in general) three medium effects that control heavy quark energy loss. These effects are 1) The Ter-Mikayelian, or massive gluon effect [15, 16], 2) Transition radiation [17] which comes from the fact that medium has finite size and 3) Medium induced energy loss [10, 16], which corresponds to the additional gluon radiation induced by the interaction of the jet with the medium.

In [18] we will show that first two effects are not important for heavy quark suppression, since their contribution is less than 10% in the final result. Therefore, in this letter, we address only the medium induced gluon radiation spectrum which is given by [10]:

$$\begin{aligned} \frac{dN^{(1)}_{ind}}{dx} &= \frac{C_F \alpha_S}{\pi} \frac{L}{\lambda_g} \int_0^\infty \frac{2\mathbf{q}^2 \mu^2 d\mathbf{q}^2}{(\frac{4Ex}{L})^2 + (\mathbf{q}^2 + M^2x^2 + m_g^2)^2} \\ &\times \int \frac{d\mathbf{k}^2 \; \theta(2x(1-x)p_\perp - |\mathbf{k}|)}{((|\mathbf{k}|-|\mathbf{q}|)^2+\mu^2)^{3/2}((|\mathbf{k}|+|\mathbf{q}|)^2+\mu^2)^{3/2}} \\ &\times \left\{ \mu^2 + (\mathbf{k}^2 - \mathbf{q}^2) \frac{\mathbf{k}^2 - M^2x^2 - m_g^2}{\mathbf{k}^2 + M^2x^2 + m_g^2} \right\}. \qquad (1) \end{aligned}$$

Here, $\mathbf{k}$ is the transverse momentum of the radiated gluon and $\mathbf{q}$ is the momentum transfer to the jet. M is heavy quark mass, $\mu = 2(\rho/2)^{1/3}$ is Debye mass, $\lambda_g = \frac{8}{9}\frac{\mu^2}{4\pi\alpha_S^2\rho}$ is mean free path [9], $m_g = \mu/\sqrt{2}$ is gluon mass and $E = \sqrt{p_\perp^2 + M^2}$ is initial heavy quark energy. We assume constant $\alpha_S = 0.3$. For central collisions we take $L = R_x = R_y = 6$ fm, and assume that ρ is given by (1+1D Bjorken longitudinal expansion [19]) $\rho = dN_g/dy\tau\pi L^2$, where $\frac{dN_g}{dy}$ is gluon rapidity density, and τ is proper time.

The energy loss was computed for both 1+1D Bjorken longitudinal expansion and using an effective *average* ρ approximation, where we replace τ by $<\tau>=\frac{L}{2}$. Since both procedures produce similar results, in this letter we present only on the computationally simpler (average ρ) results.

We note that in Eq.(1) was set to $k_{max} = 2x(1-x)p_\perp$ instead of $k_{max} = xE$ used in [10]. Numerically, there is a 20% theoretical uncertainty in R_{AA} due to the different reasonable choices of kinematical bounds.

Heavy quark suppression at RHIC and LHC. In this section we compare suppression at RHIC and LHC as a function of momentum, collision energy and gluon rapidity density dependence. In Fig. 2 we show $R_{AA}(p_\perp)$ for both charm and beauty quarks corresponding to D and B mesons in δ fragmentation. For estimates of LHC initial conditions, we consider two cases: the PHOBOS extrapolation [7] (where gluon density is projected to be approximately 60% higher than at RHIC), and the CGC prediction [8] (where the initial gluon density is predicted to be ~ 3 times higher than at RHIC). For charm quark we see that there is surprising similarity of $R_{AA}(p_\perp)$ between RHIC and LHC case, if PHOBOS extrapolation in gluon density is assumed. The similarity in suppression between these results comes from the fact that, at LHC, the enhancement in energy loss (due to the larger gluon density), is mostly compensated by the decrease of the heavy quark distribution slopes. A slightly greater suppression is obtained with CGC estimate of the initial gluon density, which leads to larger energy loss.

By comparing the charm and beauty suppressions on Fig. 2, we see that significantly less suppression is expected for beauty than for charm quarks. This is due to the following two reasons 1) from Fig. 1 we see that beauty p_T distributions have significantly smaller slopes than the charm ones, and 2) due to dead cone effect [20], the beauty energy loss is much smaller than charm energy loss, as shown on Figs.1 and 5 in [10]. This explains in large part why no significant suppression was observed for $p_\perp > 2$ GeV single electrons at RHIC [21]. In this

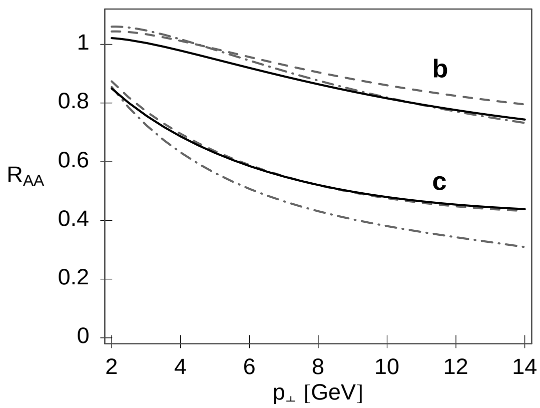

FIG. 2: The suppression ratio R_{AA} as a function of $p_{\perp}$is shown for charm (lower curves) and beauty quarks (upper curves). Full curves correspond to RHIC case ($\sqrt{s}_{NN} = 200$ GeV), while dashed and dot-dashed curves correspond to LHC case ($\sqrt{s}_{NN} = 5.5$ TeV). Dashed (dot-dashed) curves correspond to PHOBOS [7] (CGC [8]) extrapolation in gluon rapidity density.

kinematic range there is significant beauty contribution to the single electron yields and that component is essentially unquenched. Cronin and possibly collective flow effects in this low $p_{\perp} < 6$ GeV region also may play a role.

According to Fig. 2, we expect similar results for single electron suppression at both RHIC and LHC, i.e. we predict no significant suppression of single electrons at moderate p_T at LHC as well.

Our next goal is to study how the suppression is changing as a function of collision energy. For that purpose we fix the $p_{\perp}$ of quark jet to 10 GeV and look at $R_{AA}(\sqrt{s})$ as shown on Fig. 3. We see that, if gluon density extrapolates according to PHOBOS, than the $RHIC \approx LHC$ conclusion from Fig. 2 is not a coincidence. It rather seams that, in this case, the high $p_{\perp}$ charm quark suppression is essentially independent on the collision energy. In addition, the slight beauty suppression decreases as the collision energy increases. Therefore, we see that in PHOBOS extrapolation case, the 60% increase of the gluon density (and equivalently the increase in the energy loss) is not enough to compensate the decrease in the $p_{\perp}$ slope.

Slightly different situation occurs in the case of CGC extrapolation in gluon density. In this case, at LHC, we can expect 20% higher suppression for charm quarks and constant suppression for beauty quarks.

Therefore, the main conclusion following from Figs. 2 and 3, is that no significant difference between the RHIC and LHC heavy quark suppression is expected. This result is surprising. To emphasize this point, we show in Fig. 3 dot-dashed curves showing a hypothetical case in which we assume that only energy loss changes with collision energy, while heavy quark initial $p_{\perp}$ distribution remains unchanged and fixed to 200 GeV case. From this curves we see that, at LHC, the energy loss would lead to additional 0.1 decrease in R_{AA} for both PHOBOS and CGC case.

If we compare the suppression for PHOBOS and CGC case on Fig. 3, we see that at 5.5 TeV (LHC) the difference of 1000 in gluon rapidity density leads to only ≈ 0.1 difference in R_{AA}. Since the $\frac{dN_g}{dy}$ is still unknown at LHC, on Fig. 4 we show $R_{AA}(\frac{dN_g}{dy})$ for a 10 GeV D and B mesons. We see that both D and B meson suppression falls slowly with the increase of the initial gluon rapidity density.

Conclusions. In this letter we predicted the nuclear modification factor $R_{AA}(p_T, M_Q, \sqrt{s}, \frac{dN_g}{dy})$ for charm and beauty quark production in central $Au + Au$ reactions with $\sqrt{s} = 200 - 5500$ AGeV. We predict a rather weak $\sqrt{s}$ dependence in this range due to the compensation of the increasing energy loss in the more opaque sQGP and kinematic reduction of the p_T slope. Of course, it is still straightforward to deconvolute these competing effects to determine the growth of initial density with $\sqrt{s}$ and therefore differentiate between different predictions, such as CGC, of those initial conditions.

By comparing our heavy quark predictions to the suppression patterns for the neutral pions in Ref. [6] (light quark and gluon case), we expect a striking difference in the suppression pattern between light and heavy mesons. This is because the much more strongly quenched gluon jets component of light hadrons does not play a role in D and B production. The light hadron quenching pattern is therefore expected to have a stronger collision energy dependence [6].

We expect a moderate D meson suppression $R_{AA} \approx 0.5 \pm 0.1$ for the $\frac{dN_g}{dy} \approx 1000 \pm 200$ inferred from π^0. A similar suppression is expected at LHC for $1.5 - 3$ times larger $\frac{dN_g}{dy}$. Our high $p_{\perp} > 6$ GeV predictions are robust within our approach, and significant experimental deviations would pose serious challenge to the pQCD based theory of radiative energy loss in sQGP matter. Future D meson data on 200 GeV $d+Au$ and $Au+Au$ and eventually at LHC will thus enable critical consistency tests of the theory and the tomographic inferences drawn from the observed jet quenching patterns.

Acknowledgments: Authors would like to thank R. Vogt on her help with MNR code, and valuable discussions about the heavy quark production. This work is supported by the Director, Office of Science, Office of High Energy and Nuclear Physics, Division of Nuclear Physics, of the U.S. Department of Energy under Grant No. DE-FG02-93ER40764.

[1] Int.Conf. Quark Matter, Oakland, Jan. 11-17, 2004, J.Phys.G30 (2004) p.1.

[2] M. Gyulassy and L. McLerran, arXiv:nucl-th/0405013,

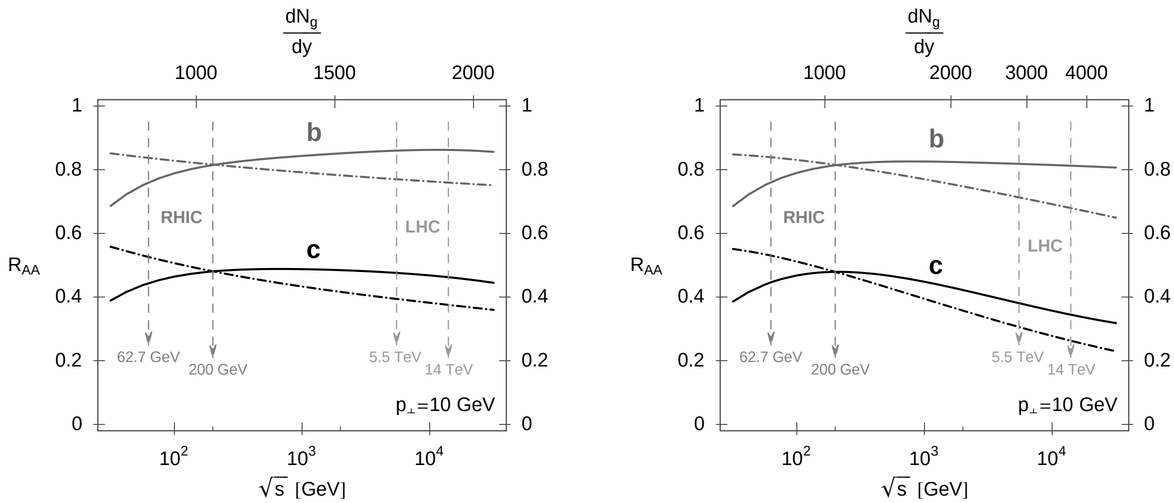

FIG. 3: The suppression ratio R_{AA} as a function of $\sqrt(s)$ is shown for 10 GeV charm (lower curves) and beauty quarks (upper curves). Left (right) figure corresponds to the PHOBOS (CGC) extrapolation in gluon rapidity density. Upper x-axis show the gluon rapidity density that corresponds to the $\sqrt(s)$ for both PHOBOS and CGC scenario. Full curves represent the case where both energy loss and initial quark $p_\perp$ distribution change with $\sqrt(s)$. Dot-dashed curves correspond to the case where only energy loss is changing with $\sqrt(s)$, while initial quark $p_\perp$ distribution is fixed at 200 GeV.

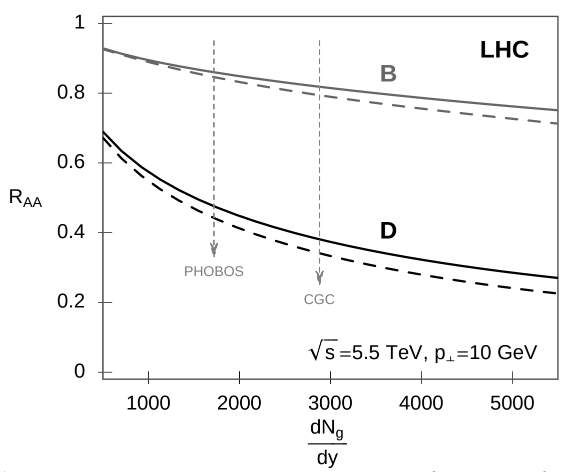

FIG. 4: The suppression ratio R_{AA} as a function of gluon density is shown for D (lower curves) and B mesons (upper curves). Solid curves are computed by assuming δ-function fragmentation while dashed curves assume Peterson fragmentation [14]. For D (B) mesons we used $\epsilon = 0.06$ ($\epsilon = 0.006$) [13].

Nucl.Phys.A in press

[3] Proc. RBRC Workshop, New Discoveries at RHIC, BNL, May 14-15, 2004, Vol. 62, BNL-72391-2004, Nucl.Phys. A in press. (see J.P. Blaizot,T.D. Lee, E. Shuryak, H. Stoecker, X.N. Wang)

[4] PHENIX collab, K. Adcox, et al, nucl-ex/0410003. BRAHMS collab, I. Aresen, nucl-ex/0410020; STAR, PHOBOS to be published.

[5] M. Gyulassy, I. Vitev, X. N. Wang and B. W. Zhang, Quark Gluon Plasma 3, (ed. R.C. Hwa and X.N. Wang, World Scientific, Singapore) p.123-191; nucl-th/0302077. A. Kovner and U. Wiedemann, p.192-248 op cit.; hep-ph/0304151 P. Jacobs and X. N. Wang, arXiv:hep-ph/0405125.

[6] I. Vitev and M. Gyulassy, Phys. Rev. Lett. **89**, 252301 (2002) [arXiv:hep-ph/0209161]; X. N. Wang and M. Gyulassy, Phys. Rev. Lett. **68**, 1480 (1992)

[7] B. B. Back et al., Phys. Rev. Lett **88**, 022302 (2002); K. Adcox et al., Phys. Rev. Lett **86**, 3500 (2001)

[8] D. Kharzeev, E. Levin, M. Nardi, hep-ph/0408050, (2004); L. McLerran, arXiv:hep-ph/0402137.

[9] M. Gyulassy, P. Levai and I. Vitev, Nucl. Phys. B **594**, 371 (2001) [arXiv:nucl-th/0006010].

[10] M. Djordjevic and M. Gyulassy, Nucl. Phys. A **733**, 265 (2004) [arXiv:nucl-th/0310076].

[11] M. Gyulassy, P. Levai and I. Vitev, Phys. Lett. B **538**, 282 (2002)

[12] M. L. Mangano, P. Nason and G.Ridolfi, Nucl. Phys. B **373**, 295 (1992)

[13] R. Vogt, Int. J. Mod. Phys. E **12**, 211 (2003)

[14] C. Peterson, D. Schlatter, I. Schmitt and Peter M. Zerwas Phys. Rev. D **27**, 105 (1983)

[15] M. Djordjevic and M. Gyulassy, Phys. Rev. C **68**, 034914 (2003)

[16] M. Djordjevic and M. Gyulassy, Phys. Lett. B **560**, 37 (2003)

[17] B.G. Zakharov, JETP Lett. **76**, 201 (2002)

[18] M. Djordjevic and M. Gyulassy, Influence of Transition Radiation to the Light and Heavy Quark R_{AA}, in preparation

[19] J. D. Bjorken, Phys. Rev. D **27**, 140 (1983)

[20] Yu. L. Dokshitzer, D.E. Kharzeev Phys. Lett. B **519**, 199 (2001)

[21] K. Adcox *et al.* [PHENIX Collaboration], Phys. Rev. Lett. **88**, 192303 (2002); [PHENIX Collaboration] (Ralf Averbeck for the collaboration), nucl-ex/0410007, (2004)